#### Research Article

Johanna-Iisebel Järvelill\*

# Development of the Narva-Jõesuu beach, mineral composition of beach deposits and destruction of the pier, southeastern coast of the Gulf of Finland

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Abstract: Narva-Jõesuu lies at the eastern southeastern coast of the Gulf of Finland, at the Estonian and Russian border. The beach is influenced by heavy winds, waves and drift ice attacks, which are seriously changing the beach. It is the longest sandy beach in Estonia and longshore drift on this beach has induced favorable conditions for the separation of heavy minerals. The aims of the study were to describe the development of the coast, discuss the influence of the destructed pier, and to identify the mineral composition of beach sands. The dynamics of the coast were mainly through comparison with older topographic maps (from the beginning of the 20th century). For mineral analysis the immersion method was applied. The heavy mineral content was found to increase from east to west. The pier was built in Narva-Jõesuu in 1987/88 for protecting the coast, but it is now broken. Consequently, storms are crashing against the coast and erosion of the sandy shore has started. Therefore, the pier should be restored to avoid further beach destruction.

**Keywords:** heavy minerals, shoreline changes, longshore movement, pier destruction

#### 1 Introduction

The Estonian coastline, which spans a distance of 3780 km, features various shore types: cliff, scarped, rocky, morainic, gravelly, sandy, silty, and artificial [1]. Among them, sandy beaches, which have experienced severe storms during the last decades, are the most vulnerable [2, 3]. Narva-Jõesuu beach is one such sandy beach on the southern coast of the Gulf of Finland, extending from Meriküla village to the outflow of the Narva River with

a length of approximately 9 km (Figure 1 and 2). A well-known health resort was established in Narva-Jõesuu in 1894. Now this area is important as the eastern border of the European Union.

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To understand beach development, knowledge on litho-morphodynamic systems is needed. Winds play a leading role in the formation of waves and are of vital significance for shore development, which is also controlled by initial topography, existing rocks, sediments, and landforms, as well as crustal movement and artificial constructions [4]. Northerly winds and drift ice have been reshaping Narva-Jõesuu for a long time, and therefore scientists and nature protection organizations must pay special attention to this area. Narva-Jõesuu beach mineral composition is studied in this paper for characterizing the beach. The topographic maps and ortophotos were compared to see the changes in the beach and connected with this the destruction of the pier in the Narva-Jõesuu beach is discussed.

The pier built in 1987/1988 increased the width and height of the coastal zone area. In 1998, a technical expert evaluation of the pier was made [5], and it was concluded that the pier had many deformations and its technical condition was very poor [6, 7]. Although it still reduces storm damage, its collapse may soon leave the coastal zone defenseless and susceptible to related disasters. For example, in China a jetty was destroyed at West Beach in Beidaihe in 2002 and after this severe erosion of the beach and the retreat of the shoreline started [8]. Modelling results showed that the jetty had worked for years as a headland to protect the beach and preserve the bay's stability. In Australia at Gold Coast, building of the grovne in the 70's stabilized the sand longshore movement [9]. Furthermore, another groyne was built to prevent the erosion, which was nevertheless still lasting.

<sup>\*</sup>Corresponding Author: Johanna-Iisebel Järvelill: Tallinn University Tallinn, Estonia; Email: iisebel@hotmail.com

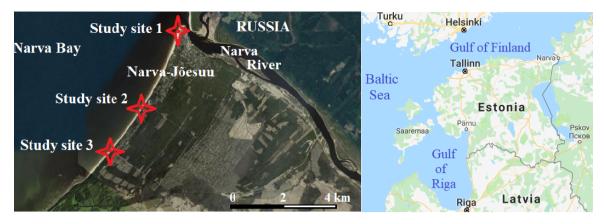
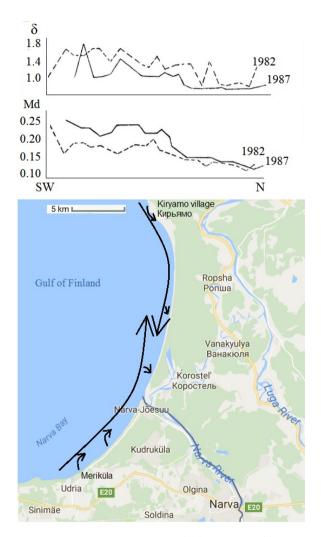


Figure 1: Location of Narva-Jõesuu beach and the sampling sites for mineralogical analyses along the north-eastern coast of Estonia.



**Figure 2:** Changes of median diameter (Md) and sorting ( $\delta$ ) of grains along the shoreline of Narva Bay during 1982–1987 (Orviku and Romm, 1992). Direction of the movement of beach sediments indicated by an arrow extending to Russia (modified from Orviku and Romm, 1992).

### 2 Study area

Narva-Jõesuu is a famous health resort located in northeastern Estonia near the Russian border. The area is influenced by uneven land uplift (0.8 mm/yr at Narva-Jõesuu, [10] and sediments have developed under the conditions of water level changes during the alternating lake (Baltic Ice Lake deglaciation to 11 600 cal yr BP and Ancylus Lake 10 700–9800 cal yr BP) and marine (Yoldia 11 600–10 700 cal yr BP, Littorina 9800–4400 cal yr BP and Limnea Seas 4400 cal yr BP up to the present) stages [11].

The study area has a straightened accumulation coast, and Narva River runs through the middle. Narva-Jõesuu beach starts from Meriküla near Udria and extends to Russia (Figure 1, 2), with a sandy shore of 50-60 m wide. The main sand sources are nearby abrasion areas and river sediments. The role of alluvial sediments weakened after the Narva Hydropower Station and a water reservoir were built upstream in the 1950s. Therefore, the beach suffers from sand deficit and the shore is vulnerable to storms, which have destroyed not only the beach, but also the foredunes and older dunes. At the end of the 1980s, the reconstruction of the sandy beach was started; the construction of an artificial beach with an underwater sandbar and a pier was started, but it has not yet been completed [12] (Figure 3). According to Orviku [6] the pier is not finished due to the bad construction manners, which have caused the waves destruction. The elaboration of the pier was not done. The reinforced concrete panels, which were supposed to cover the reconstruction, are still lying on the beach.





Figure 3: The pier in Narva-Jõesuu in 1998 (A, [7]) and the crushed pier in 2016 (B, author).

## 2.1 Study history and storm damage to the coast

Several studies have investigated the storm damage to Narva-Jõesuu beach [13–15]. Since the 18th century, great effort has been made to regulate the water flow of Narva River. In 1770, wooden protective walls were erected on the river banks, and in 1889, a depression was excavated at the river mouth. In the second half of the 19th century, the reconstruction of the Narva-Jõesuu harbor and the building of a 1860 m long and 8.5 deep pier were started. However, the pier was destroyed during World War II [5, 7].

The first turbines of the Narva hydropower station were put into operation in 1955, and the Narva water reservoir with an area of about 191 km<sup>2</sup> was constructed, regulating sediment flow to the sea. As expected, with the decreased river flow, smaller amounts of sediments were transported to the sea [7]. In 1975 high masses of sand were washed away, rendering the beach low and wet. Heavy

storms in 1975, 1982, 1983, and 1986 moved sand masses away from the beach, and a 2.5 km stretch of the coast west of Narva River was damaged. Foredunes were destroyed during the winter storm in 1986 [15].

These events of heavy damages urged the Institute of Geology at the *Academy of Sciences* of the *Estonian SSR to* start research for shore protection [14]. Accordingly, a coastal protection project was compiled in 1983. The project aimed at pumping sand from the mouth of Narva River with a pipe, transporting additional sand from the Kurtna Kame Field to Narva-Jõesuu beach, and building a new pier in the river mouth. Unfortunately, this project was never finished [15]. Orviku [6] pointed out the previously mentioned bad pier reconstruction as the cause of the wave destruction, the building did not follow the project.

Orviku and Romm [15] studied litho-morphodynamical changes of the beach in Narva-Jõesuu during 1982–1987 (Figure 2). Orviku and Romm [15] concluded that the average size of particles in beach deposits increased with proximity to the west of the mouth of Narva River. Mediumgrained sand were found to move increase along the shore towards the north, indicative of the expansion of the area of beach erosion in the same direction.

During 1993-1994, the Meteorological and Hydrological Institute of Estonia conducted measurements of an area from the pier to the south-west, considering 45 profiles up to a depth of 5 m. The results were compared with the measurements taken in 1988. Control measurements were also taken near the river outflow in 1993 and in the south-western part of the beach in 1994. The results of these measurements indicated that the shoreline had moved towards land in the area starting from the river and up to 125 m from the river. In contrast, the shoreline had moved towards the sea in an area 125-1050 m from the river, with the most shoreline changes in the area 500 m from the river outflow. The results of measurements taken in 1994 showed that, during 1988-1994, the shoreline had moved in an area 1 km from the outflow and southwestward from there towards the sea. The construction of the pier and the material transported had increased the height and the width of the beach. In 1995 the Geological Survey of Estonia started coastal monitoring at Narva-Jõesuu. Monitoring profiles were partially located at the same sites as the measurement profiles of the pier project in 1988 [16, 17].

Measurements taken in 2008 within the framework of the State Monitoring Programme showed that the coastline near the pier moved 1.5 m seaward during 2003–2008. This could be attributed to sand blown in on foredunes by wind. Abrasion, transport, and accumulation of sediments near Narva River are influenced by the levels of the sea and river. With high sea levels, river water also rises, and the elevated river level induces strong flow, which facilitates the movement of larger amounts of sediments, and therefore increases abrasion of the shore. Finer materials are carried deeper into the sea. Sediments in the coastal zone are moved by waves, and the movement becomes more intensive in the breaker zone. Higher levels of water and strong winds from the west expand the river mouth. These processes continue until the wind weakens or changes direction [7, 18].

According to Leppik [13], the highest water level in Narva-Jõesuu was observed in September 1897, up to 2.353 m above sea level (asl), and the lowest level (-0.85 m) was observed in 1923. Before the 1970s, the level was recorded to be above 1.50 m only five times. Comparing the area of Narva-Jõesuu between 1981 and 2007, inland movement of 80 500 m² of land and seaward movement of 66 000 m² have occurred. During 1982–2007, the shoreline southwest from the pier has moved 70 m seaward [7].

#### 3 Methods

In this study, shoreline changes and the mineral composition of beach deposits were investigated, and compared with previous results [15, 19]. The beach was excavated up to a depth of 1 m in the beach face or backshore zone to collect samples (about 1 kg each sample) and determine heavy mineral concentrations in deeper zones in 2014. Three main sites with 10 samples were chosen for mineral analysis (Figure 1). Mineral analysis is in this work connected with the coastal dynamics as the mineral content is influenced by the coastal processes (winds, storms, water level changes), causing also heavy mineral concentrations (HMC). Analysis of topographic maps was used for characterizing coastline changes by the changes in area for different sections of the shore. The dynamics of the coast were mainly investigated by comparison with existing measurements and topographic maps (from the beginning of the 20th century).

Fractions for mineral analysis were sieved with an Analysette 3 Vibratory Sieve Shaker PRO using a sieve set with eight fractions: 2000, 1000, 500, 250, 125, 100, 63, and 36  $\mu$ m. For mineral analysis, fractions 125–250, and 63–100  $\mu$ m were used. In addition, light and heavy (over 2.8 g/cm³) mineral suites were separated. The immersion method was applied, using liquids with refractive indexes of 1.54 and 1.64. About 300 and 500 mineral grains were counted for the light and heavy subfractions, respectively,

in each mineral suite [20, 21]. Ore minerals are the opaques in the samples.

#### 4 Results

According to the granulometry the samples are dominated by sands with fraction of 125–250  $\mu m$  with 58.8%. The fraction 250–500  $\mu m$  is with content of 21.1%. Fractions 100–125  $\mu m$  and 500–1000  $\mu m$  were found with contents 2.6% and 2.2%, respectively. Other fractions were with contents under 1%.

Results of mineral analyses (Table 1) show that quartz is the most dominant with 76.6% in the fraction of 125-250 µm, followed by feldspars with 19.7%. In the finer, 63–100 µm, fraction (30 cm deep), the content of quartz is 78.3% and that of feldspars 21.4% on average. In the heavy subfraction, the content of carbonates is high (up to 33.3%). In the finer fraction, carbonates account for less than 5.0%. Samples show quite a high content of ore minerals with 8.8% in the 125-250  $\mu m$  fraction and 17.3% in the 63–100 µm fraction. At site 3, the contents of extreme heavy minerals are up to 57.4%. Furthermore, the medium heavy mineral content increases from the pier towards the west, with 1.04% near the pier, 7.4% in the middle part of Narva-Jõesuu beach, and 22.8% at site 3. The content of ore minerals near the pier on the surface of the beach is lower than in sites 2 and 3 (2.5%, increasing towards the west, up to 19.7% in site 2 and 11.7% in site 3).

The average content of heavy minerals shows wide variability from east to west. The lowest content of heavy minerals (0.4%) was found in one sample from site 1 near Narva River (Figure 1). The content increased up to almost 60% in one sample from the 60 cm deep excavation at site 3, which reflects intense storm activity. In surface samples, the heavy mineral content shows a similar trend: an increase from 1.9% at site 1 to 10.4% at site 2 (6.9% at site 3).

#### 5 Discussion

The contents of light minerals of Narva-Jõesuu beach and bottom sediments of Narva Bay [19] are similar. The average content of quartz is 76.6% in the beach samples and 75.3% in the bay samples, with feldspars accounting for 19.7% and 22.2%, respectively. The bottom sediments of Narva Bay have a lower heavy mineral content compared to the coastal samples, with averages of 1.1% and 4.6%, respectively. The beach is more influenced by heavy mineral

Table 1: Mineral composition of sediments at Narva-Jõesuu beach in the fractions of 125-250 μm and 63-100 μm (%)

	Site 1	Site 2	Site3	Mean	63-100 μm (site 2)
Distance from the Narva River mouth	385 m	3733 m	5624 m		3733 m
	Light miner	als			
Quartz	66.9	73.5	89.4	76.6	78.3
Feldspars	32.7	16.9	9.5	19.7	21.4
Micas	0.3	0.9	0.3	0.5	0.0
Carbonates	0.1	8.2	0.8	3.0	0.0
Glauconite	0.0	0.6	0.0	0.2	0.0
Aggregates	0.0	0.0	0.0	0.0	0.3
	Heavy mine	rals			
Iron hydroxides	7.0	7.5	11.1	8.5	0.0
Pyrite	0.0	0.0	3.4	1.1	0.0
Carbonates	35.0	27.2	29.7	30.6	1.5
Barite	16.9	8.4	6.5	10.6	0.0
Leucoxene	0.0	0.0	0.4	0.1	0.0
Anatase	0.0	0.0	0.0	0.0	0.0
Muscovite	0.2	1.4	0.2	0.6	0.0
Brown biotite	8.7	19.1	8.9	12.2	0.0
Chlorides	0.6	1.1	1.0	0.9	4.2
Ore minerals	5.3	12.7	8.4	8.8	17.3
Garnets	0.3	1.8	0.6	0.9	28.9
Zircon	0.0	0.0	0.0	0.0	9.8
Tourmaline	0.0	0.7	0.0	0.2	1.7
Apatite	0.0	0.2	0.0	0.1	7.3
Corund	0.0	0.0	0.0	0.0	0.0
Rutile	0.0	0.0	0.0	0.0	1.3
Titanite	0.0	0.1	0.0	0.0	1.5
Epidotes	0.8	1.1	0.6	0.8	3.5
Andalusite	1.4	0.0	0.0	0.5	0.0
Amphiboles	0.0	11.9	14.2	8.7	19.3
Pyroxenes	11.5	6.6	2.2	6.8	0.0
Calcite	0.0	0.0	0.3	0.1	3.5
Dolomite	0.0	0.0	7.8	2.6	0.0
Kyanite	12.4	0.0	5.0	5.8	0.0
Aggregates	0.0	0.0	0.0	0.0	0.0
Heavy subfraction	1.0	7.4	22.8	10.4	-

accumulation, showing that more intensive processes are taking place in the active zone of sample locations. The beach sediments could be more eroded, showing heavy mineral enrichment, as pointed out by El Banna [22].

Narva Bay results by Lutt and Popova [19] has a higher content of garnets (9.1%) compared to that on the beach (0.9%). The content of amphiboles is also higher in Narva Bay samples (18.8%) compared to that on the beach (8.7%). In contrast, the content of pyroxenes is higher in the beach samples (6.8%) than in the bay samples (0.5%). The content of carbonates is also higher in the beach sedi-

ments, with an average of 3% (33.3% in heavy fraction) as compared against 1.5% in the bottom sediments. Overall, beach sediments appear to be more influenced by the local carbonate bedrock.

The coastal erosion connected to the longshore sediments movement is considered more intensive on the Baltic Sea coast than in the Gulf of Riga [23, 24]. Eberhards et al. [24] stated that the erosion has been increased due to storms on the Latvian coast. They compared the rates of years 1935-2007 and erosion has been 1 to 3 times higher in the years of 1992–2007. This erosion increase is also seen in the Narva-Jõesuu beach.

Orviku and Romm [15] reported longshore sediment movement and compensating coastal currents with nearshore flow moving along Narva Bay from west to east and further to the north. This movement begins from Lower Paleozoic rocks of Udria cliff in the western part of the bay. They highlighted the increase of particle size towards the west of the river, which is typical of areas with dynamic equilibrium (Figure 2). Light minerals were carried towards the pier, where sand accumulation can be observed. Therefore, the heavy mineral concentrations are higher in sites 2 and 3. Fine materials have also been washed away from the beach. As hydrodynamic activity becomes weaker, the coarseness of the particles in deposits decreases [15]. According to Frihy [25], a high rate of erosion is connected with heavy minerals increase and finer grain size of sand. Coastal processes selectively remove coarser grains with lower density, leaving behind small grains with high density. These erosion areas were observed westwards from the Narva River (sites 2 and 3).

When examining the lithodynamics of recent sediments in Narva Bay, it should be noted that the hydrodynamics of this basin is quite active because the bay is a slightly sloping inverted curve that is open to the prevailing north-westerly winds and the height of wind-driven waves is up to 3.5 m. Quite small offshore slopes should also be taken into consideration. All these factors create favorable conditions for longshore transport and compensating coastal currents. As the migration and differentiation of the material in the coastal area are regulated almost exclusively by the movement of the bodies of water by means of currents and undulation when the waves hit the shore, the results of the above-mentioned research can be used to study lithodynamic processes that led to the formation of coastal deposits [15].

Frihy [25] and Komar [26] found a relationship between the decrease in the content of opaques, zircon, rutile, and garnets and longshore distance from the river mouth. Furthermore, the augite and hornblende contents were found to increase in shoreline areas undergoing accretion. An increase of opaques, zircon, rutile, and garnets was also observed in the Narva-Jõesuu samples. For example, the average content of opaques is 5.3% near the river and as high as 12.7% at site 2. A westward increase in the content of amphiboles could be observed in the samples: it is 0.0% at site 1, but it increases to an average of 14.2% at site 3. Frihy [25] found that opaques and garnets plus zircon are concentrated in areas of shoreline erosion. Zircon is almost absent at site 1, reflecting the accumulation zone. The content of heavy minerals in the samples indi-

cates their connection with local Ordovician rocks (high percentage of carbonates and presence of glauconite).

## 5.1 Coastline changes in the Narva-Jõesuu pier area

Narva Bay is characterized by erosion processes and the extension of the erosion area is caused by the increase of the median diameter of beach sand and the shift of the central sand zone along the shore to the north [15]. In 1987, construction works associated with a coast protection project and a pier project were started but, as already mentioned, they were not completed [6, 7] (Figure 3).

The strategic environmental assessment of Narva Town comprehensive plan in 2019 [27] concluded that the pier should be reconstructed. According to the city government preliminary draft the sheet piles and the concrete covering them should be removed and a 388 m long pier built (the old pier is 400 m). This needs environmental impact assessment and important is to evaluate the cross border influence as it lies on the border of Estonia and Russia.

The coastline near the pier on the beach of Narva-Jõesuu has changed during the last years (Figure 4). The pier was built to increase the width and height of the coastal zone and to reduce storm destruction. Unfortunately, the pier is currently broken, sediments can by-pass the broken pier and the increase of the coastal zone area has almost come to a halt. The seaward movement of the shoreline has decreased and the sand accumulation area that was south-westward from the pier in 2007 is now

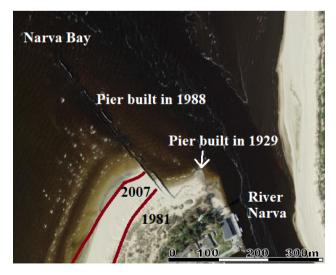


Figure 4: Coastlines in 1981 and 2007 (according to Kask and Kask, 2012) and coastline in 2018 (orthophoto is used as background), showing the decreased movement seaward.

spreading and the sand is being carried from the west to east to Russia or partly to the deeper sea by riverflow. To save the beach from further destruction, the pier should be restored and its construction should be completed. Important is that, when the pier should be destructed, the long-shore sediment movement could block the Narva River mouth, as it happened in Australia before the two groynes were built [9], where the sand by-passing was intense, resulting in channel migration and sometimes the closure of the mouth. When the pier is destroyed, in addition to the siltation of ship channel, loss of beach width will be drastic and soon, beach infrastructure and buildings closer to the sea will be in high danger.

#### **6 Conclusions**

In this study, the longest sandy beach in Estonia, with rather high content of heavy minerals, was investigated. The beach is influenced by the longshore movement of sediments and coastal currents with nearshore flow moving along Narva Bay from west to east and further to the north. The heavy mineral content increases from the Narva River to the west, showing higher concentrations at sites 2 and 3. The medium heavy mineral content is high in the Narva-Jõesuu beach samples. Changes to the sandy beach are highly influenced by the old damaged pier. Movement of the shoreline towards the sea has stopped due to the by-passing of the storm eroded sediments through the broken pier. Therefore, according to these new results the pier should be restored for avoiding further beach destruction.

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